Resolving the $B \to \phi K^*$ Polarization Anomaly

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The experimental observation of sizable transverse components for $B \to \phi K^*$ decay is in strong contrast to all other VV modes, and poses a challenge to our understanding of B decay dynamics. Observing that the gluon emitted from $b \to sg^{(*)}$ chromodipole transition is transverse, we give a heuristic model where the transverse ϕ descends from the emitted gluon, hence similar phenomena should occur for $B \to \omega K^*$ but not for $B \to \rho^0 K^*$. New physics in bsg chromodipole coupling, perhaps needed for the $\bar{B} \to \phi K_S$ CP violation anomaly, may lead to different patterns of CP and T violation in transverse components of $\bar{B} \to \phi \bar{K}^*$, $\omega \bar{K}^*$ decays.

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Two-body charmless $B \to PP$, PV and VV decays, where P, V stand for light pseudoscalar and vector mesons, can provide us access to quark mixing and CP violation parameters, and insight into strong dynamics. The VV modes are more difficult to study as they involve s-, p- and d-wave components. Some modes have appeared recently [1, 2], bringing forth, however, the so-called $B \to \phi K^*$ polarization anomaly. Both Belle [3] and BaBar [4, 5] experiments have observed significant transverse components of $B \to \phi K^*$ decay, while theoretically it is argued [6] that these should be $1/m_b^2$ suppressed. We do not know whether it is related to the "CP violation anomaly" in $\bar{B} \to \phi K_S$, but since Belle [7] and BaBar [8] are at variance on the latter, with BaBar in agreement with Standard Model (SM) expectations, the ϕK^* polarization anomaly may be viewed as more urgent. So far there are no convincing solutions.

In this paper we offer a possible solution. We note that on-shell $b \to sg$ decay has a rate of a few $\times 10^{-3}$ [9], and the emitted gluon is dominantly transverse. Viewing the transverse ϕ meson (ϕ_T) as a leading single particle gluon fragment, it is conceivable that $B \to \phi_T K_T^*$ at few $\times 10^{-6}$ can be generated. The feeddown fraction is two orders of magnitude smaller than the $B \to K^*\gamma$ case, which is about 13% of $b \to s\gamma$ rate [1]. It follows that one should find transverse component for $B \to \omega K^*$ mode but not for ρK^*, $\rho\rho$. The mechanism also opens a window onto possible New Physics (NP) in chromodipole bsg coupling, which may have already manifested itself in the ϕK_S CP violation anomaly.

The $1/m_b$ suppression of transverse component can be seen heuristically as follows. The longitudinal polarization for a vector meson V can be approximated by $\epsilon_L^\mu \to p^\mu/m_V$ up to $O(m_V/E)$. Since $E_{1,2} \sim M_B/2$ for charmless $B \to V_1 V_2$ modes, we see that $\epsilon_{1L}\cdot\epsilon_{2L} \to p_1\cdot p_2/m_1 m_2$ is of order M_B^2, whereas $\epsilon_{1T}\cdot\epsilon_{2T} = -1$. The dominance of longitudinal component seems to be borne out by $B \to \rho\rho$ [10, 11] and ρK^* [4], but it apparently breaks down for $B \to \phi K^*$. In the linear polarization (CP) basis, the experimental results are [3, 4, 5]

$$|f_0|^2 = 0.43 \pm 0.09 \pm 0.04 \qquad \text{(Belle)},$$
$$|f_0|^2 = 0.52 \pm 0.05 \pm 0.02 \qquad \text{(BaBar)}, \tag{1}$$

for the longitudinal fraction, and

$$|f_\perp|^2 = 0.41 \pm 0.10 \pm 0.04 \qquad \text{(Belle)},$$
$$|f_\perp|^2 = 0.22 \pm 0.05 \pm 0.02 \qquad \text{(BaBar)}, \tag{2}$$

for the CP-odd fraction.

It has been argued [6] that the chromodipole $b \to s\bar{s}s$ 4-quark operator O_{12} cannot contribute to transverse ϕ formation. This is because the s quark from $b \to s$ dipole transition is paired with the $\bar{s}$ quark from the virtual gluon. Since the latter is transverse, one would always have a mismatch of quark helicities. Our proposal also starts from the transverse nature of such a gluon, but we focus on the case where it is close to the mass shell. Being rather energetic, such a gluon reaches the B meson surface in less than 10^{-24} s without much interaction (perturbative vacuum), but then it must shed its color. Its "essence" should be able to penetrate the meson surface at ease, i.e. the energy, momentum and perhaps its angular momentum would depart from the B meson carcass "instantly", leaving behind some hadronic scale disturbance to balance the color.

The above heuristic picture is depicted in Fig. 1. The system recoiling against ϕ_T consists of the fast s quark, the spectator $\bar{q}$, and the color octet remnant (the minimum would be two soft gluons) of the gluon shown as the ellipse, which is rather complicated. But if it ends up as

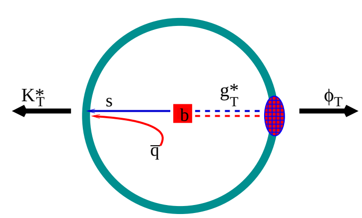

FIG. 1: Heuristic picture for transverse ϕ emission. The gluon from $b \to s$ chromodipole is mostly transverse, and could emit a transverse ϕ meson. The singlet nature of the gluon implies that this process does not affect charged vector meson or ρ^0.

a K^*, it would also be transverse by angular momentum conservation.

Let us start from the relevant effective Hamiltonian

$$H_{\text{eff}} = -\frac{G_f}{\sqrt{2}} V_{ts}^* V_{tb} \Big\{ \sum_{n=3-10} c_n O_n + c_{12} \frac{g_s}{8\pi^2} m_b \bar{s}_i \sigma_{\mu\nu} (1+\gamma_5) T_{ij}^a G^{a\mu\nu} b_j \Big\}, \quad (3)$$

where n =3–6 and 7–10 label strong and electroweak penguins, respectively, and the chromodipole operator is explicitly dimension 5. While O_{3-10} are local, the 4-quark operator O_{12} generated by the chromodipole term is nonlocal, indicating its special character. After all, the gluon from the parton level $b \to sg$ process can propagate a long distance, giving rise to an inclusive rate $\sim (2-3) \times 10^{-3}$ in SM. *The process is the QCD analog of the famous $b \to s\gamma$ transition*, but its effect has been rather elusive experimentally, while theorists tend to treat it as an afterthought within the operator framework.

The "on-shell" gluon is dominantly transverse. Taking $q^2 \sim 1$ GeV^2 as an effective gluon mass, such an energetic ($E \sim m_b/2$) gluon traversing the hadronic medium cannot be distinguished from a colinear color octet $q\bar{q}$ pair. In any case, it traverses the hadronic sized B meson carcass in $\sim 10^{-24}$ s, much shorter than the hadronic time scale of $\sim 10^{-23}$ s, hence has little time to change its nature. When it reaches the meson boundary, although the confinement energy would quickly rise, so long the effective color octet $q\bar{q}$ pair leaves behind the same color octet charge to settle its "debt", it can depart the B meson carcass in a color singlet configuration and hadronize. The remaining hadronic scale color octet "disturbance" (minimum of two soft gluons) balances the color octet fast s quark plus spectator $\bar{q}$ quark, and the system takes the hadronic time scale of $\sim 10^{-23}$ s to settle into a particular hadronic configuration, with some amplitude as a single K^* meson. Thus, our picture is the combined effect of (transverse) gluon fragmentation plus recoil side recombination.

Our argument is not perturbative, but boils down to an Ansatz of replacing $T_{ij}^a G^{a\mu\nu}$ first by (ignoring constant factors) $T_{ij}^a q^\mu \varepsilon_{g^*}^{*a\nu}$, then by $\delta_{ij} p_\phi^\mu \varepsilon_\phi^{*\nu}$ where p_ϕ^μ is the ϕ momentum and differs from q^μ only by a hadronic scale momentum. Finally, we parametrize this mechanism of ϕ_T generation by a hadronization parameter κ,

$$\frac{\kappa}{m_B} c_{12} \, p_\phi^\nu \epsilon_{\phi T}^{*\mu} \langle K_T^* | \bar{s}_i i\sigma_{\mu\nu} (1+\gamma_5) b_j | B \rangle, \quad (4)$$

together with a factor $-\frac{G_F}{\sqrt{2}} V_{ts}^* V_{tb} f_\phi m_\phi$. The $f_\phi m_\phi$ factor is to conform with the operators O_{3-10} which produce ϕ from a vector current. The rather complicated perturbative and nonperturbative hadronization has been simplified into a single parameter, which we take as real since there is no clear physical cut. Note that we have absorbed $g_s m_b$ etc. into κ. To keep κ dimensionless, the additional power of $1/m_B$ is in anticipation of a similar factor from the hadronic matrix element.

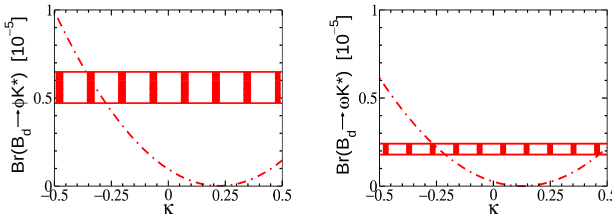

FIG. 2: (a) $\mathcal{B}(B \to \phi K^*)$ and (b) $\mathcal{B}(B \to \omega K^*)$ vs hadronization parameter κ in longitudinal (solid) and transverse (dot-dash) components.

We now write down the longitudinal (0), parallel ($\parallel$) and perpendicular ($\perp$) amplitudes for $B \to \phi K^*$,

$$\mathcal{A}_{i,\perp} \propto \Big\{ \Big[\sum_{j=3,4,5} (a_j \mp a_j') - \frac{1}{2} \sum_{j=7,9,10} (a_j \mp a_j') \Big] X_\lambda + (c_{12} \mp c_{12}') \Big[\kappa_\lambda \tilde{F}_\lambda + \frac{\alpha_s}{4\pi} \frac{m_b^2}{q^2} \tilde{S}_\lambda \Big] \Big\}, \quad (5)$$

in linear polarization basis, where $\lambda = i, \perp$ with $i = 0, \parallel$. Epitomizing our Ansatz which does not feed the longitudinal mode, $\kappa_0 \approx 0$, while $\kappa_\parallel \approx \kappa_\perp = \kappa$. The hadronic parameters

$$X_0 = \frac{m_B + m_K^*}{2} A_1 \, x - \frac{m_\phi m_{K^*}}{m_B + m_{K^*}} A_2 \, (x^2 - 1),$$
$$X_\parallel = -\frac{m_B + m_K^*}{\sqrt{2}} A_1,$$
$$X_\perp = -\frac{m_\phi m_{K^*}}{m_B + m_{K^*}} V \, \sqrt{2(x^2-1)}, \quad (6)$$

are $B \to K^*$ form factor combinations. Noticing that $x = p_\phi \cdot p_{K^*} / m_\phi m_{K^*}$ is of order m_b^2, one can already see the $1/m_b$ suppression at work when one compares $X_{\parallel,\perp}$ with X_0. The usual chromodipole hadronic parameters $\tilde{S}_\lambda$ are form factor combinations analogous to X_λ, and arise from the $B \to K^*$ dipole in the matrix element of O_{12}. Again, $\tilde{S}_0$ is larger than the other two. Our model gives additional hadronic parameters $\tilde{F}_\parallel$ and $\tilde{F}_\perp$ from Eq. (4), which are roughly $X_\parallel$ and $-X_\perp$, but with dipole form factors. Note that in Eq. (5) we have kept opposite chirality operators which are vanishingly small in SM, but may arise from NP.

The branching fractions for $B \to \phi K^*$ in different polarization components are plotted in Fig. 2(a). The longitudinal component is independent of our new hadronic parameter κ, but receives some suppression from interference with usual chromodipole term. We have computed the coefficients a_j and c_{12} at $\mu = m_b$ scale, which, together with light-cone sum rule form factors [12], give longitudinal rate consistent with data. We plot the sum of parallel and perpendicular components since both are transverse and are of similar strength in our Ansatz.

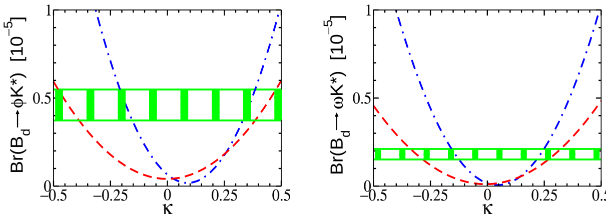

FIG. 3: (a) $\mathcal{B}(B \to \phi K^*)$ and (b) $\mathcal{B}(B \to \omega K^*)$ vs κ for $\lambda = 0$ (solid), $\|$ (dotdash) and $\perp$ (dash), with CP phase $\sigma = \pi/2$.

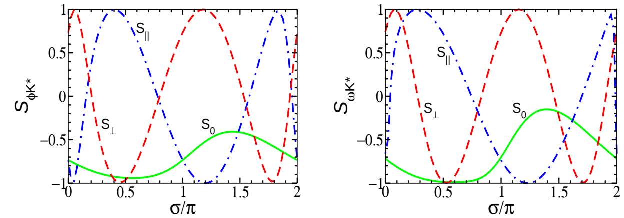

FIG. 4: $\mathcal{S}_\lambda$ vs CP phase σ for (a) ϕK^{*0} and (b) ωK^{*0} for $\lambda = 0$ (solid), $\|$ (dotdash) and $\perp$ (dash), with $\kappa = +0.25$.

With our somewhat *ad hoc* term, the transverse component rises to 5×10^{-6} for $\kappa \sim -0.25$, and is enhanced slightly by usual chromodipole term. The longitudinal rate can be further reduced if one uses different form factors where A_2/A_1 is larger, making X_0 smaller. Alternatively, there is much uncertainty in the hadronic parameter $\tilde{S}_0/q^2$. We illustrate the destructive interference and show, in Fig. 2(a), the range of reduction when q^2/m_b^2 drops from 1/3 to 1/4. It should be clear that there is no need for NP, and our Ansatz is able to accommodate the ϕK^* polarization anomaly within SM.

The Ansatz allows some immediate predictions. The transverse gluon fragmentation picture should apply to ω_T emission. Besides SU(3) breaking effects, one gains a $\sqrt{2}$ isospin factor. The usual contributions to the decay amplitudes are now more involved, where the tree contributions distinguish between charged and neutral modes. Further, besides ω emission with $B \to K^*$ transition terms, one now also has K^* production with $B \to \omega$ transition. Our Ansatz contributes clearly only to the former. We plot the $B \to \omega K^*$ results vs κ (treated on same footing as ϕK^* case) in Fig. 2(b). We use $\phi_3 \equiv \arg V_{ub}^* \simeq 60^\circ$ such that the charged and neutral modes have very similar rates. The $B \to \omega K^*$ rate is predicted to be of order 4×10^{-6}, and the transverse components could dominate. Note that our mechanism would not feed $\rho^0 K^*$ channels, nor $\rho^\pm K^*$. Thus, another consequence of our model is that the ρK^* and $\rho\rho$ modes would be predominantly longitudinal, in agreement with data [4, 10, 11].

Although our model can be viewed as effective within SM, the ϕK_S CP violation anomaly, if it persists, may call for the need for NP. We have proposed [13] a NP model with a light, flavor mixed "strangebeauty" right-handed squark, the $\widetilde{sb}_{1R}$, which brings in strong $\widetilde{sb}_{1R}$-$\tilde{g}$ penguin loop, together with a new CP violation phase σ from the $\tilde{s}_R$-$\tilde{b}_R$ squark sector. The model can be motivated [14] by approximate Abelian flavor symmetry which implies large right-handed s-b mixing, transferred to the squark sector, and drives the $\widetilde{sb}_{1R}$ light. It can be as light as 100–200 GeV with common squark mass at TeV scale. We showed [13] that for $m_{\widetilde{sb}_{1R}} \sim 200$ GeV, $m_{\tilde{g}} \sim 500$ GeV and $\sigma \sim \pi/4 - \pi/2$, the model could account for the ϕK_S CP violation anomaly, with a host of predictions. Basically, in formulas analogous to Eq. (5), the primed terms are generated. We observed [14] that the dominant effect is in c'_{12} (and $c'_{7,11}$), all other terms are small. Thus, it seems natural to consider the impact of this NP model on ϕK^* and ωK^*.

With the above parameter values and $\sigma = 90^\circ$, we plot the branching fractions of $B \to \phi K^*$ and ωK^* vs κ in Figs. 3(a) and 3(b), respectively. From Fig. 3(a) we see that $\kappa < 0$ is no longer viable since, contrary to experiment, the parallel rate becomes too large compared with the perpendicular one. We take $\sigma = 90^\circ$ because otherwise the parallel rate rises too slowly for $\kappa > 0$. But $\kappa \sim +0.25$ can be viewed as a solution of the ϕK^* polarization anomaly in this NP model. With κ fixed this way, the ωK^* results of Fig. 3(b) are predictions, and previous remarks continue to apply. Note that the parallel component may be the largest.

The interest in discussing NP is not so much about the polarization anomaly itself, but to predict associated CP violating asymmetries. Since the B_d lifetime difference is negligible, and since we do not consider rescattering and associated strong phases, the main observable is the mixing dependent CP asymmetry for $\bar{B}^0 \to \phi K^{*0}$ and $\omega \bar{K}^{*0}$ in each polarization component,

$$S_\lambda = \frac{2\xi \, \mathrm{Im}(\frac{q}{p}\, \overline{\mathcal{A}}_\lambda \mathcal{A}_\lambda^*)}{\overline{\mathcal{A}}_\lambda^2 + \mathcal{A}_\lambda^2}, \tag{7}$$

which is the coefficient of the $\sin \Delta m \Delta t$ oscillation term, q/p contains the B^0 mixing phase $\sin 2\phi_1$, and $\overline{\mathcal{A}}_\lambda$ is the amplitude of the conjugate process. Taking $\kappa = 0.25$ as example, we plot $\mathcal{S}_\lambda$ vs CP phase σ in Figs. 4(a) and 4(b) for ϕK^{*0} and ωK^{*0}, respectively.

The σ dependence can be understood as follows. Let us write a particular polarization amplitude as $\mathcal{A} = a\, e^{i\theta_1} e^{i\delta_1} + b\, e^{i\theta_2} e^{i\delta_2}$, where the first term is the SM contribution sans chromodipole penguin (hence CP phase $\theta_1 \cong 0$), while the second term is $\propto c_{12} \mp c'_{12}$ (hence θ_2 depends on σ). Assuming that strong δ phases are small, and taking the ϕK^{*0} case as example, it is easy to see that for S_0, one has $a^2 \gg b^2$. The leading effect is then the SM CP phase in B_d mixing (modulo the CP eigenvalue ξ), plus a simple ($\sim \sin \sigma$) modulation around this constant value. For $S_\parallel$ and $S_\perp$, however, one has $a^2 \ll b^2$ because of $1/m_b$ suppression of usual terms. Thus, $S_\parallel$

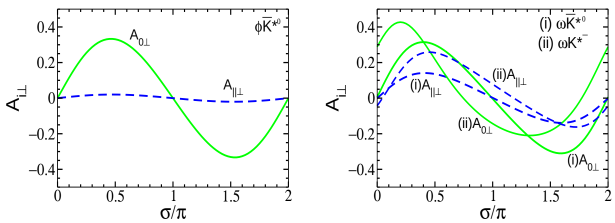

FIG. 5: T violation parameter $A_{i\perp}$ vs σ for $B \to$ (a) ϕK^* and (b) ωK^* for $i = 0$ (solid), $\parallel$ (dash) components.

and $S_\perp$ is determined by $(c_{12} \mp c'_{12})^2$ (see Eq. (5)) hence close to $\sin 2\sigma$ variation from the SM expectation value of $\mp \sin 2\phi_1 \simeq \mp 0.74$. Note that for $\sigma \simeq \pi/2$, one would find $S_\parallel$ and $S_\perp$ to be of similar strength to expectation, *but with opposite sign*, which is analogous to $S_{\phi K_S}$ [13]. Unfortunately one is not free from hadronic uncertainties. It is important to separate the parallel and perpendicular components to make such measurements, for otherwise they would dilute each other out.

Another intriguing measure, which needs neither oscillation measurement nor tagging, is the triple product T-violation parameter [15],

$$A_{i\perp} = \frac{1}{2}\left(\frac{\mathrm{Im}\,(\mathcal{A}_\perp \mathcal{A}_i^*)}{\sum |\mathcal{A}_\lambda|^2} + \frac{\mathrm{Im}\,(\overline{\mathcal{A}}_\perp \overline{\mathcal{A}}_i^*)}{\sum |\overline{\mathcal{A}}_\lambda|^2}\right), \tag{8}$$

from interference pattern in angular analysis. We plot $A_{i\perp}$ vs σ in Figs. 5(a) and 5(b) for $B \to \phi K^*$ and ωK^*, respectively. For ϕK^*, there is little difference between charged and neutral mode. But for ωK^*, the tree contribution brings in the SM CP phase ϕ_3, and there is some difference between charged vs neutral modes. We note with interest that BaBar has measured [5] $A_{0\perp} = 0.11 \pm 0.05 \pm 0.01$ and $A_{\parallel\perp} = -0.02 \pm 0.04 \pm 0.01$ for $B \to \phi K^*$, which is consistent with our results. The agreement is not yet very significant. However, given the error bars, significant results may soon become available with improved data sets.

Some remarks are in order. The $b \to sg$ parton level process, with non-negligible rate at few $\times 10^{-3}$ level [9] (reaching 10^{-2} in the NP case with $\sigma = 90°$), has so far been rather elusive for direct access. But given that it is the QCD analog of $b \to s\gamma$, it is certainly quite important. It would be amusing if the polarization anomaly would turn out to be the harbinger of $b \to s$ penguin involving on-shell gluon emission. Second, the recoil system against ϕ_T is in general complicated. One could consider searching for $\phi_T/\omega_T + (Kn\pi)_V$, or even a recoil tensor meson. Conversely, the transverse gluon could fragment into any flavor singlet low-mass hadronic system that has total spin 1. One may therefore wish to search for $B \to$ "V"K_T^* where "V" stands for some low-mass singlet vector configuration. Third, it would be nice if the on-shell $b \to sg$ penguin could help resolve the problem of large $B \to \eta' K$ rate and the *finite* $B \to \omega K$ rate. But it is unclear how the mechanism we outlined could feed longitudinal vector meson production. Perhaps the polarization can be left behind in form of hadronic excitation as the gluon "energy packet" leaves the B meson carcass. Finally, we note that inclusive $b\bar{q} \to q_1\bar{q}_2$ annihilation rate is slightly larger [9] than $b \to sg$, which has been invoked [6] for generating the transverse components of $B \to \phi K^*$. However, the proposal is not predictive and needs additional arguments for $B \to \rho K^*$. Likewise, the $D_s^{(*)}\bar{D}^{(*)}$ rescattering picture [16] would also have trouble with ρK^*.

In conclusion, we have given an *ad hoc* but simple one parameter model where transverse components for $B \to \phi K^*$ descend from on-shell $b \to sg$, where ϕ_T is a transverse gluon fragment. Similar behavior is predicted for $B \to \omega K^*$ but not ρK^* and $\rho\rho$ modes. Although the picture is generic, New Physics CP phases could generate opposite sign CP violation in $B \to \phi K^*$, ωK^* transverse components, as well as T-violating triple product observables.

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